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Hybrid Technologies for Clandestine Electric Reconnaissance Vehicles (CERV)

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ABSTRACT

Future Military ground vehicle power trains can benefit from a hybrid-electric drive approach, particularly in packaging flexibility where drive train components can be modular and conveniently distributed. This paper describes the development and testing of a suite of power conversion modules for use in a Tactical Vehicle Hybrid Power System. The primary technical advancement goals of this effort are the addition of silent mobility and the addition of exportable electric power. Other potential benefits include increased fuel efficiency, reduced drive train weight, complexity, and manufacturing cost, and increased mission capabilities.

INTRODUCTION

RCT Systems has developed and demonstrated a suite of power conversion modules for use in a Tactical Vehicle Hybrid Power System. This suite of components is designed to provide enhanced capabilities to a Tactical Vehicle. These components work together as a system to provide: electric powered traction for the vehicle, either for silent mobility or traction assist; a means of extracting stored energy from a vehicle battery system for use during silent watch activities, both for onboard and off-board use; a means for utilizing the vehicle engine and fuel for the generation of AC and DC electric power to serve off-board AC loads and onboard DC loads while stationary; and a means of charging the onboard vehicle battery system from an off-board AC system or utility grid. The components consist of an inline Motor/Generator, a Motor Generator Controller, an Off-board Power Converter, and a Vehicle Power Converter. The system was developed to meet or exceed all of the initial Joint Light Tactical Vehicle (JLTV) objective electric power requirements for on-board as well as export power, providing power for all anticipated weapon/sensor systems, and a future "silent move" capability. Each of the components, their specifications and test results will be described herein.

SYSTEM DESIGN

A typical system arrangement on a vehicle is shown pictorially in Figure 1, in contrast to the typical conventionally powered vehicle in Figure 2.

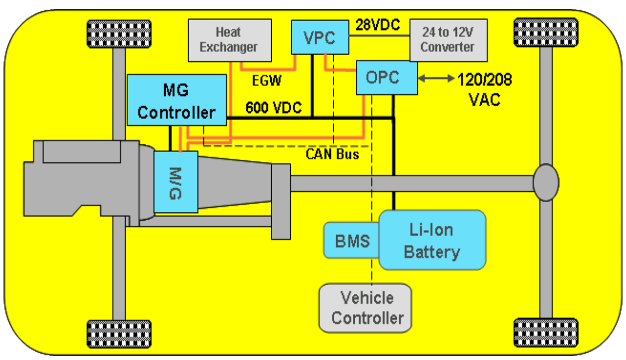

Figure 1
Tactical Vehicle Hybrid Power System

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14. ABSTRACT
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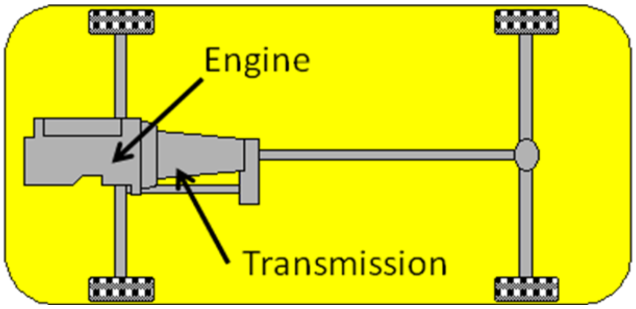


Figure 2
Conventionally Powered Vehicle

The Motor/Generator (M/G) provides up to 60kW of traction power to the drive train, or up to 60kW of DC power to the vehicle's 600VDC bus. The Motor/Generator Controller (MGC is a bi-directional electronic power converter which is the interface between the Motor/Generator and the vehicle's 600VDC bus and controls the mode and power flow from/to the Motor/Generator.

The Off-Board Power Converter (OPC) is a bi-directional inverter which provides an interface between the vehicle's 600VDC bus and 120/240/208 VAC off-board power systems. This Off-Board Power Converter can be used to charge vehicle batteries, or to provide up to 30kW of exportable AC power to an off-board load utilizing energy from the onboard battery system or the vehicle's engine by means of the Motor/Generator. The Vehicle Power Converter (VPC) is a uni-directional converter that converts power from the vehicle's 600VDC bus to 28V for use in onboard auxiliary systems and to charge the vehicle's starting battery.

Potential Modes of Operation

There are a number of potential modes of operation for the system, depending on arrangement:

- **Normal Driving Mode**

The hybrid electric machinery starts the engine, provides power boost from the battery during acceleration, and recharges the battery during cruise and deceleration. The battery provides accessory load power.

- **Silent Mobility Mode**

The engine is off and the hybrid electric machinery, powered by the battery, acts like an electric vehicle traction motor.

- **Engine-Driven APU Mode**

At standstill, the engine drives the hybrid electric machinery to recharge the batteries and drive higher power auxiliary loads.

- **Silent Watch Mode**

At standstill, the engine and hybrid electric machinery are unpowered and the battery provides power to auxiliary loads or is recharged from off-board "plug in" sources.

MOTOR/GENERATOR

The M/G shown in Figure 3 is a 60kW Surface Permanent Magnet machine (SPM). This type of machine design is best suited for applications with:

- Variable speed and load
- Constant or increasing torque
- Typical of actuators, pumps/fans, and some Integrated Starter Generators (ISGs)

The benefits of SPM machines are:

- High power density
- High efficiency and power factor over wide load and speed range

The machine was designed with an SAE 3 Flange connection on each end (but other diameters/SAE Flange sizes are available), and intended to be located in-line "tucked in" between the engine bell housing and transmission for this parallel hybrid configuration. The reason for the in-line design was to insure the robustness of the vehicle, in that the vehicle can still be driven in the event of a casualty to the M/G because the engine is still coupled to the transmission. The design requirements for this parallel hybrid system to permit "silent move" operations had a significant impact on the M/G weight. In this mode, the battery provides power to the M/G as a motor (similar to a hybrid vehicle running on the battery) to drive the vehicle for short distances (distance impacts overall battery system sizing). This resulted in a robust system with high continuous torque values (similar to a large SUV) and added weight, over a similarly rated ISG that RCT systems had developed for the FCS program (65kW at 65 lbs). The FCS ISG was used either as a starter or generator for a series hybrid vehicle where the generator was providing power to in-wheel traction motors. Clearly if there is no requirement for "silent move" the ISG is a lighter weight alternative to the M/G.

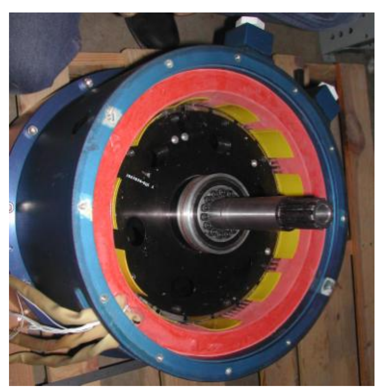


Figure 3
End view of Motor Generator

MOTOR/GENERATOR CONTROLLER (MGC)

The MGC is a 63 kW galvanically isolated, bi-directional AC/DC inverter used to interface between the vehicle 600V battery bus, and the M/G. The MGC is used to drive the M/G in propulsion mode and to convert its output to DC power in the generating mode.

Figure 4
Motor/Generator Controller (MGC)

OFF-BOARD POWER CONVERTER (OPC)

The 30 kW OPC (figure 5) provides bi-directional, galvanically isolated DC/AC converter for 120/208VAC 50/60Hz power from the 600V Vehicle DC Bus. This two mode module allows the vehicle to provide export power (Generator mode) as a voltage source with characteristics defined in MIL-STD-1332 as a tactical mobile generator capable of providing single and three phase loads with 120/208VAC at 50/60Hz. In the Plug-in Hybrid (PHEV) mode, the OPC operates as a load to power the Vehicle DC Bus from an external 120/208VAC at 50/60Hz power source for battery charging and operation of other on board equipment. The OPC and high voltage Energy Storage system operate in concert with the Motor-Generator and Controller to form the Vehicle DC Bus. When operating in PHEV mode from external power, the OPC provides power to the Vehicle DC Bus if either the Energy Storage System, or Motor-Generator and Controller are not available.

Figure 5
Off-Board Power Converter (OPC)

VEHICLE POWER CONVERTER (VPC)

The VPC (figure 6) is an isolated DC/DC converter designed to take power from the vehicle 600 VDC high voltage battery bus and generate up to 8.3 kW of power at 24 VDC for vehicle auxiliary bus loads (lights, radios, etc.) and to maintain charge on the system 24V battery.

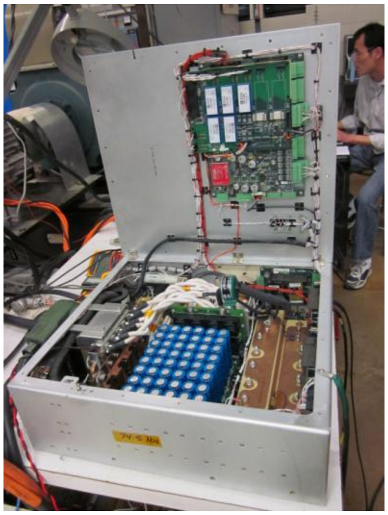
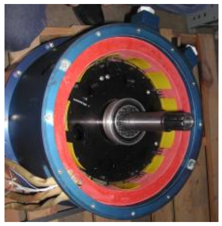
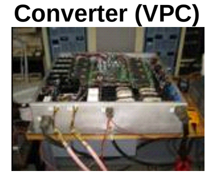


Figure 6
Vehicle Power Converter (VPC)

SYSTEM SPECIFICATIONS

A summary sheet with key specifications for all system components is shown in Table 1 below.

Table 1. Tactical Hybrid Vehicle Power System Specifications

	Motor/Generator 	Motor/Generator Controller 	Off Board Power Converter (OPC)  Export Power		Vehicle Power Converter (VPC)  In Vehicle DC/DC Conversion
Dimensions	16" D x 8.75" L	14" x 18" x 8"	31" x 33" x 8"		21" x 19" x 7"
Weight	172 lbs	53 lbs	245 lbs		97 lbs
System operating voltage	318 VRMS line to line M/G output	Interfaces with M/G and vehicle 600VDC bus bi-directional	Interfaces with 600VDC vehicle bus and 120/240/208 AC off board systems, bi-directional		Converts power from 600VDC vehicle bus to 28 VDC
Average Power and Conditions	60 KW (81HP) AC Output at 2300 rpm min	60kW AC output to M/G from 600VDC vehicle bus/battery. 60kW DC output from M/G to 600VDC vehicle bus/battery.	30kW, 0.8pf to AC off board loads from 600VDC vehicle bus/battery. 30kW AC off board source to 600VDC vehicle bus/battery.		8.4kW to 28VDC loads from 600VDC vehicle bus/battery
Output Current Rating	170A peak - 325A peak, transient		1 pu continuous 2 pu, 5 sec, fault clearing		300ADC
Efficiency (Full Power)	≥ 95%	≥ 96%	≥ 93%		≥ 91%
Power Quality			MIL-STD-1332, Type I Class I, Mode I		MIL-STD-704
Cooling	EGW, 50/50, 1.5gpm				
Operating Range	-46 C to +54C ambient air, -40C to +70C coolant				
OPC Operating as a Voltage Source (Generator Mode)					
Electrical frequency/range		Frequency	50/60Hz	48-52/58-62 Hz	
3Φ 4 wire plus GND		Output Voltage/Power	120/208VAC	0 - 30kW, at 0.8pf	
1Φ 3 wire plus GND		Output Voltage/Power	120/240VAC	0 - 20kW, at 0.8pf	
1Φ 2 wire plus GND		Output Voltage/Power	120VAC	0 - 10kW, at 0.8pf	
OPC Operating as a Load (PHEV Mode)					
Operating as 3Φ Load		Voltage/Power	208VAC	0 - 30kW	
Operating as 1Φ Load		Voltage/Power	240VAC	0 - 20kW	
Operating as 1Φ Load		Voltage/Power	120VAC	0 - 2kW	
M/G Interface	SAE J617 #3 flanges standard SAE #1 or #2 size, or custom available				
M/G Torque	300 lb-ft, max (407 n-m)				
M/G Speed	0 to 4000 rpm				
Enclosure Protection	Inline installation	IP 67 compatible			
Communications	CAN Bus, Class C, SAE J1939				
Shock (Design)	MIL-STD-810 Method 516.5 for ground vehicles				
Vibration (Design)	MIL-STD-810 Figure 514.5C-1				
EMI (Design)	MIL-STD-461, MIL-STD-464				
Electrical Isolation	MIL-STD-917, Isolated, galvanic				

SYSTEM TESTS

System testing, to measure key performance parameters, was completed at RCT Systems facilities in the spring of 2011. The test setup is shown below in figures 7 and 8. During this test, all power converters were connected to a common DC bus, which included a 600V (nominal) lead-acid battery pack. Resistive loads were used for the VPC and OPC outputs.

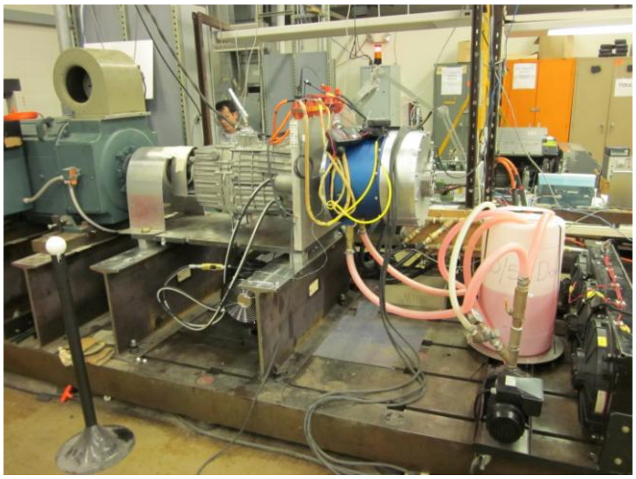


Figure 7
Tactical Hybrid Powertrain System Testing

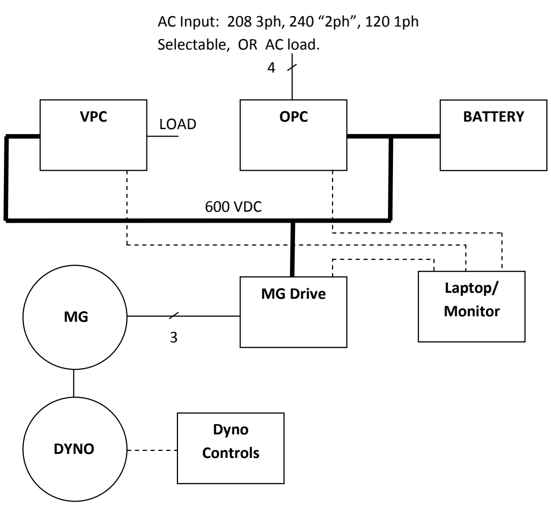


Figure 8
System Test Block Diagram

The anticipated next step is to transfer the system to TARDEC for installation and testing at the ***Ground Vehicle Integration Center*** (GVIC).

SUMMARY

This integrated Tactical Vehicle Hybrid Power System was initially developed for the Air Force Research Laboratory (AFRL) for a special vehicle application. During the program, the power goals were set to meet the initial JLTV on-board and off-board power requirements. At one point in the development there was Congressional support for integration into an MRAP vehicle. Due to program constraints and funding this did not happen. The system power level is completely scalable, and as discussed above the M/G could be replace by an ISG saving considerable weight if the assumed requirement for silent mobility was not a consideration. Factory testing of this initial prototype system identified several component improvements that can be made. Testing at TARDEC’s GVIC is expected in the next year.

The benefits of an integrated system such as this are many. The parallel hybrid architecture provides for vehicle mobility under all conditions, even in the event of battle damage that might affect the electrical system components. The 30 kW OPC allows for both vehicle battery charging (PHEV Mode) and can power off-board loads. The integrated, survivable, mobile, on-the-go nature of this vehicle power can support field radars, communication, weapons and sensor systems, as well as charging rechargeable batteries for individual soldier or squad use. These are requirements that would otherwise have to be powered by towed Tactical Quiet Generators (TQG’s).

ACKNOWLEDGEMENT

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AUTHORS

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Mr. Wagner is Vice President of Engineering for RCT Systems with over 28 years experience in electronics and electro-mechanical product design and development. His experience includes power electronics, signal conditioning, data acquisition, digital design, microprocessors, and programming. Mr. Wagner has extensive experience in the deployment of heavy-duty electric and hybrid-electric power trains for use in transit buses, and the associated battery-charging infrastructure. Mr. Wagner is a member of the Industry Advisory Board for the Florida State Center for Advanced Power Systems (CAPS), and a member of the Steering Committee for the Electric Power Research Institute (EPRI) National Electric Vehicle Infrastructure Working Council. He is a registered Professional Engineer, and a member of the IEEE. He holds BSEE and MSEE degrees from Lehigh University.

Yuntao Xu, PhD

Dr. Xu is a Power and Control System Engineer at RCT Systems, with over 15 years of experience in developing power electronic converters and variable speed drives. He developed the utility interface and conducted intensive study of a mutually coupled switched reluctance machine used in a wind power generation system during his doctoral work. He developed the system controller for a high power rotary UPS, designed hardware and software for a single phase photovoltaic inverter, and was responsible for the controller design and software development for a high power fuel cell inverter system. More recently, he has been involved with the power circuit design, control algorithm development, and integration of various power converters for vehicle applications, including the off-board power converter, the variable speed drive for the integrated motor/generator, and the vehicle power converter. He has an MS and PhD, Electric Power Engineering, both from Rensselaer Polytechnic Institute.

Richard M. Young

Richard (Mack) Young is an Advisory Engineer at RCT Systems, with 34 years of experience designing and applying control electronics and motor drives for the Westinghouse/ Northrop Grumman Electronic Systems Sector. He was the engineering manager of the electric bus programs and was responsible for the design, test and deployment of commercial electric and hybrid buses. He has designed several motor drives including a 500 HP drive for sonar pulse power using a flywheel for energy storage. Most recently, as an Advisory Engineer for the Northrop Grumman Oceanic Division, he was the lead electrical field engineer on ASDS and was directly responsible for the test, modification and integration of the battery based propulsion and power distribution systems. Mr. Young holds a BSEE from the California State Polytechnic University and a MSEE from The George Washington University.

James L. Munro, PE

James Munro is a Power Systems Engineer at RCT Systems with over 20 years experience in developing solid state power conversion products for Military and Commercial applications. The products developed include high power three-phase stationary power generation equipment used in distributed power applications, a 100HP and 230HP motor controller for an Electric Vehicle Power Train, and a permanent magnet brushless DC motor controller for underwater propulsion. The three phase power generation products have been used in the field with micro turbine and fuel cell systems rated from 50kVA to 375kVA. James is also a lead designer and systems engineer for the development of 100kW high voltage DC/DC power conversion modules for the Integrated Power Systems Program within the US Navy. Mr. Munro holds a BSEE from West Virginia University, an MSEE from Johns Hopkins University and has a Professional Engineer's License and has 5 patents. Mr. Munro is a Licensed Professional Engineer and a member of IEEE Industry Applications and Power Electronics Societies.

Dennis P. Mahoney, PE

Mr. Mahoney is Vice President, Business Development, RCT Systems. A Vietnam veteran, he served for 30 years in the US Navy as an Engineering Duty Officer. Relevant tours include Chief Engineer on a Destroyer; Head Design Division, Pearl Harbor Naval Shipyard; Director, Naval Sea Systems Command (NAVSEA), Hull, Mechanical and Electrical group, responsible for all non-nuclear ship mechanical and electrical systems and components. He was the first Program Manager for the Zumwalt (DDG-1000) Class guided missile destroyer. He was head of the Naval Postgraduate School Naval/Mechanical Engineering program, and Professor of Naval Construction and Engineering at MIT. He holds BS & MS ChemE degrees from Iowa State University, as well as SM Nuclear Eng and Ocean Eng degrees from MIT. He is a registered Professional Engineer.

ABOUT RCT SYSTEMS

RCT Systems is a leading developer of high power, high power density power electronics, motors and drives for demanding applications in the defense and aerospace sector. RCT Systems is the former Applied Technology division of the Satcon Technology Corporation which was sold to a group of private investors in January of 2010. RCT maintains a staff of over 40 industry leading engineers, scientists, and technicians and has 16,000 square feet of manufacturing, laboratory and office space located in Linthicum, Maryland near the Baltimore Washington International Thurgood Marshall Airport (BWI). RCT is an ISO 9001:2008 registered company.